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GPFARM modeling of corn yield and residual soil nitrate-N

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Abstract

US agriculture is facing low commodity prices to farmers because of foreign competition, environmental concerns, and weather fluctuations such as droughts. Producers need to quickly evaluate the marketplace and select appropriate management systems for their farms and ranches. The Great Plains Framework for Agricultural Resource Management (GPFARM) decision support system was developed to assist farmers and ranchers with key strategic management decisions, but requires additional testing before general adoption by the agricultural community. This paper evaluated GPFARM simulation of continuous corn (*Zea mays* L.) yields and soil residual nitrates under irrigated and partially irrigated conditions, fertilized and non-fertilized applications, and high and low planting densities. Validation results for a 3-year field study indicated the model could simulate corn yields and soil residual $\text{NO}_3\text{-N}$ without bias at the $P < 0.05$ level with R^2 values for predicted versus observed corn yields and soil residual $\text{NO}_3\text{-N}$ of 0.830 and 0.383, respectively. Mean extended modeling error (EME), a measure of modeling error extending outside the error range of the validation measurements was 168 and 25.2 kg/ha for corn grain yields and soil residual $\text{NO}_3\text{-N}$, respectively. The EME results further showed that the scatter around the simulated versus observed 1:1 lines for soil residual $\text{NO}_3\text{-N}$ versus corn yields was 53.5 and 19.9% of the mean sum of the absolute residuals, respectively, suggesting higher modeling error with the residual $\text{NO}_3\text{-N}$. The EME method also effectively separated modeling error from error that could be accounted for by uncertainty in the experimental validation data set. Agricultural producers, consultants, and action agencies should consider these validation results and potential errors when using the model to predict corn yields and related soil $\text{NO}_3\text{-N}$ estimates in strategic management planning and environmental assessment studies.

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Keywords: Whole-farm management; Soil–crop models; Environmental quality; Decision support systems; Model validation

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1. Introduction

Farmers in the United States must increasingly use management techniques that enhance economic crop yields, yet protect the environment from soil erosion and nitrate leaching. Producers must adapt to fluctuations in local weather patterns and commodity prices in the World market, plus react to trends in Federal and State legislation, and sometimes to negative perceptions by the urban public. The ability to quickly modify farm and ranch management practices to cope with the weather, the global economy; new cropping, pest management, and tillage systems; and new legislation while protecting soil, air, and water resources, may determine whether an agricultural enterprise system survives or perishes.

The complexity of agricultural management problems calls for a comprehensive and integrated knowledge base of the whole system and suitable analysis tools in making decisions. The Great Plains Framework for Agricultural Resource Management (GPFARM) decision support system was developed for use by farmers and ranchers to help with strategic planning of on-farm management (Shaffer et al., 2000; Ascough et al., 2002b; McMaster et al., 2002a,b). The overall goal of GPFARM is to determine medium and long-term effects of current and alternate cropping, ranching, or integrated farming systems on economic and environmental sustainability. The program is also capable of analyzing changes in management practices associated with these systems, such as the level of tillage and residue cover, dates of planting, manure and fertilizer applications, chemical weed control, and water applications on cropland and grazing management on rangeland. GPFARM allows managers to design and compare alternate long-term strategies on the computer before implementing them in the field. Before applying GPFARM to actual on-farm management situations, producers need to know how well the model simulates key components such as crop yields and environmental impacts. In particular, irrigated agriculture is a highly managed enterprise with high crop yield potentials and equally high potentials for environmental impacts such as $\text{NO}_3\text{-N}$ leaching to ground water. The objectives of this paper are to validate the GPFARM model for corn (*Zea mays* L.) grown under a range of management strategies for water, nitrogen, and planting density and identify any areas for improvement in their simulation.

2. The GPFARM science model

2.1. Introduction

GPFARM consists of an integrated set of linked modules designed for decision support at the whole-farm level (Fig. 1). The user interface, simulation package, economics component, output/risk analysis, and information system comprise the major components. These operate as an integrated tool to provide the user with information on crop yields, environmental impacts, and economics for strategic planning on a whole-farm or parts of a farm. The user interface is MS Windows-based and is written in Visual C++ (Ascough et al., 2002a,b) and the simulation package consists of an object-oriented C++ framework that calls processed-based simulation modules written in FORTRAN and Visual Basic (VB) (Shaffer et al., 2000). Fig. 2 shows the integrated FORTRAN and VB submodel

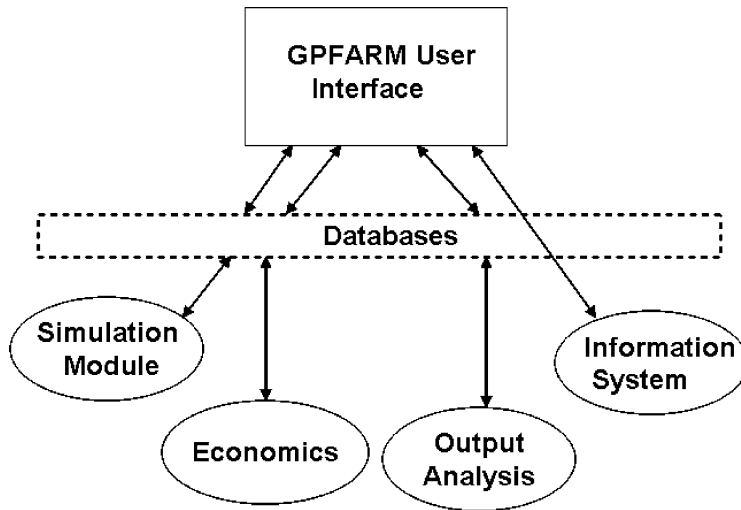


Fig. 1. Primary modules contained in GPFARM DSS model.

components of the simulation module. A weed dynamics component written in VB operates independently of the FORTRAN code to estimate the effects of weed pressure and population dynamics on crop yield (Canner et al., 1998; Canner et al., 2002). The integrated FORTRAN components simulate crop growth as a function of solar radia-

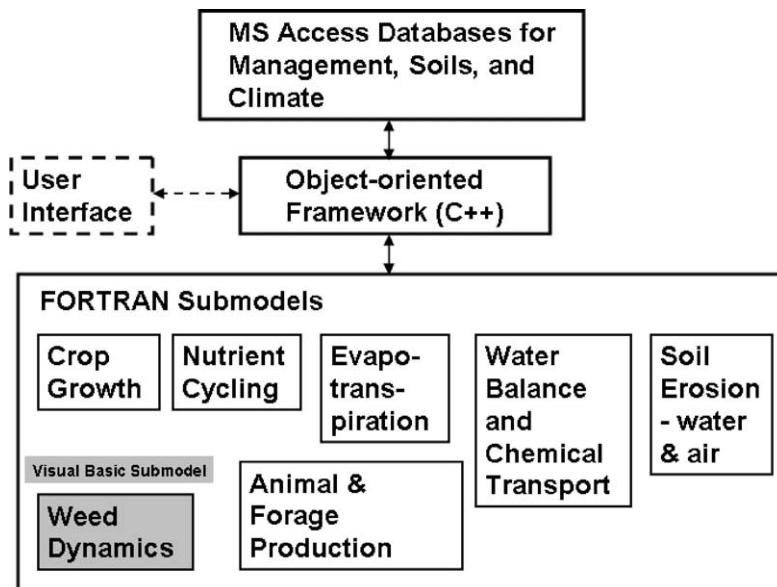


Fig. 2. Submodel components of GPFARM simulation module.

tion and stresses from temperature, water, and nitrogen. In addition, carbon and nitrogen cycling, evapotranspiration, soil water movement and solute transport, soil erosion, and pesticide degradation and transport are simulated as part of the integrated package (Nachabe and Ahuja, 1996; Farahani and Ahuja, 1996; Ahuja et al., 2000; Shaffer et al., 2001).

2.2. GPFARM crop growth module

The crop growth module in GPFARM is derived from the crop component of the Water Erosion Prediction Project (WEPP) model (Arnold et al., 1995; Deer-Ascough et al., 1998). The WEPP crop growth model was derived from the Environmental Policy Integrated Climate (EPIC) crop growth component (Williams et al., 1984, 1989). The GPFARM version has been further modified and incorporates some elements from the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992). A single model is used for simulating several crops by changing model parameters. Stress factors for water, nitrogen (N), and temperature are computed using inputs from other independent modules within GPFARM (McMaster et al., 2003).

2.2.1. Phenological development and potential biomass production

Phenological development of the crop is based on thermal time using daily heat unit accumulation (McMaster et al., 2003). Biomass distribution among leaves, stems, seeds, and roots is based on phenological growth stage. Several relationships are used in determining daily potential biomass production. Interception of photosynthetic active radiation (PAR) is estimated with Beer's law (Monsi and Saeki, 1953). Potential biomass production per day is estimated by multiplying the intercepted PAR with a crop-specific energy to biomass conversion ratio (Montieth, 1977).

2.2.2. Actual biomass production and stress factors

Actual daily biomass accumulation is determined by Liebig's Law of the Minimum. The daily potential biomass accumulation (ΔPB_i) is adjusted daily if one of the plant stress factors (water, N, or temperature) is less than 1.0 using the equation:

$$\Delta B_i = (\Delta PB_i)(REG) \quad (1)$$

where REG is the crop growth regulating factor (the minimum of the water, N, and temperature stress factors) calculated for day i . The adjusted daily total biomass production (ΔB_i) is accumulated through the growing season.

The water stress factor is computed by considering supply and demand in the equation:

$$WS = \frac{\sum_{l=1}^{n_l} u_l}{E_p} \quad (2)$$

where WS is the water stress factor (0–1) for the day, u_l is plant water use in soil layer l (mm), n_l is the number of soil layers, and E_p is the daily potential plant transpiration (mm).

The N stress factor is computed by considering the N demand for biomass production and amount of plant N uptake in the equation:

$$NS = \frac{\sum_{l=1}^{m_1} V_l}{N_p} \quad (3)$$

where NS is the N stress factor (0–1) for the day, V_l is the plant N ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) uptake in soil layer l (kg/ha), and N_p is the daily plant N demand for that day. N_p is calculated as a percentage of daily total biomass production and varies depending on crop growth stage based on plant parameters for emergence, mid-season, and maturity.

The temperature stress factor is computed with the equation:

$$TS = \sin \left(\frac{\pi}{2} \left(\frac{(T_{\text{ave}} - T_{\text{base}})}{(T_{\text{opt}} - T_{\text{base}})} \right) \right) \quad (4)$$

where TS is the temperature stress factor (0–1), T_{ave} is the average daily temperature ($^{\circ}\text{C}$), T_{base} is the base temperature for the crop ($^{\circ}\text{C}$), and T_{opt} is the optimum temperature for the crop ($^{\circ}\text{C}$).

2.2.3. Crop yield

Crop yield for annual crops is estimated using the harvest index concept, which is adjusted throughout the growing season according to water stress constraints:

$$YLD = (HIA)(B_{\text{AG}}) \quad (5)$$

where YLD is crop yield (kg/m^2), HIA is adjusted harvest index at harvest, and B_{AG} is cumulative above ground biomass (kg/m^2) before senescence occurs. Harvest index increases nonlinearly from zero at planting using the equation:

$$HI_i = \text{HIO}(\text{HUFH}_i - \text{HUFH}_{i-1}) \quad (6)$$

where HI_i is the harvest index on day i , HIO is the harvest index under favorable growing conditions, and HUFH is the heat unit factor that affects harvest index for day i and the previous day $i - 1$. The harvest index heat unit is computed with the equation:

$$\text{HUFH}_i = \frac{\text{HUI}_i}{\text{HUI}_i + e^{(6.50 - 10.0 \text{HUI}_i)}} \quad (7)$$

The constants in Eq. (7) are set to allow HUFH_i to increase from 0.1 at $\text{HUI}_i = 0.5$ –0.92 at $\text{HUI}_i = 0.9$. This is consistent with economic yield development of grain crops which produce most of their economic yield in the second half of the growing season.

Most grain crops are particularly sensitive to water stress near the growth stage of anthesis (Doorenbos and Kassam, 1979). The harvest index is affected by water stress using the equation:

$$\text{HIA}_i = \frac{\text{HI}_i}{1.0 + \text{WSYF}_j(\text{FHU}_i)(0.9 - \text{WS}_i)} \quad (8)$$

where HIA_i is the adjusted harvest index, WSYF is a crop parameter expressing drought sensitivity (assumed to be a constant 0.01), FHU is a function of crop stage, and WS is

the water stress factor for day i . The maximum value for HIA_i is limited to HI_i within GPFARM.

Greater detail on the above equations and other equations not discussed (e.g. canopy height, canopy cover, LAI, crop stage factor) can be found in [Kiniry et al. \(1992\)](#); [Arnold et al. \(1995\)](#); [Deer-Ascough et al. \(1998\)](#); [McMaster et al. \(2003\)](#).

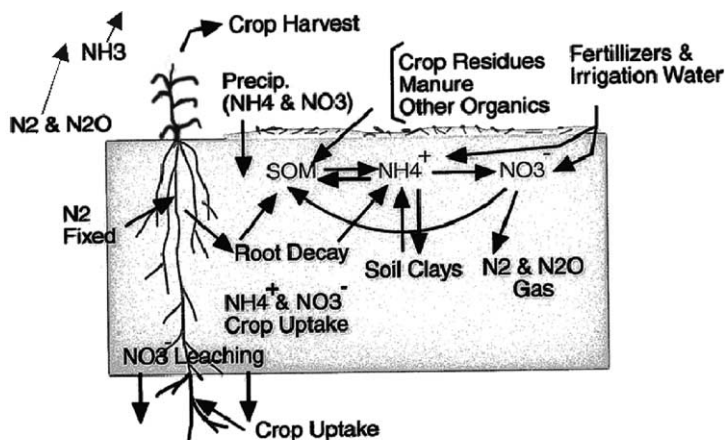
2.3. GPFARM carbon and nitrogen cycle module

The GPFARM carbon/nitrogen (C/N) model contains integrated modules for C/N cycling processes on the soil surface and within the soil profile ([Fig. 3](#); [Shaffer and Ma, 2001](#)). These modules were adapted from the Nitrate Leaching and Economics Analysis Package (NLEAP) model ([Shaffer et al., 1991, 2001](#); [Ma and Shaffer, 2001](#)) and simulate mineralization/sequestration of soil organic matter (SOM); decomposition (mineralization/immobilization) of crop residues, manure, other organics; and transformations of inorganic nitrogen fertilizers applied to the soil surface or incorporated into the soil profile. The modules account for nitrification, denitrification, and gaseous losses of NH_3 , and estimate NH_4 -N and NO_3 -N available for surface runoff, residual NO_3 -N available for leaching from the crop root zone, and soil NO_3 -N and NH_4 -N available for crop uptake. The C/N cycle modules interact with GPFARM modules for water and solute transport, crop growth and N uptake, surface runoff and erosion, and range land production.

2.3.1. Mineralization/sequestration of SOM

Mineralization of SOM is simulated using a two-pool model containing a fast readily-decomposable pool and a slower humus pool ([Fig. 4](#)). The decay process is first order as shown in [Eq. \(9\)](#).

$$NOMR = k_{omr} \times SOM \times TFAC \times WFAC \times \frac{0.58}{10} \quad (9)$$



From Shaffer and Ma (2001), p. 15.

Fig. 3. Carbon and nitrogen (C/N) cycling in GPFARM.

GPFARM mineralization portion of C/N cycle

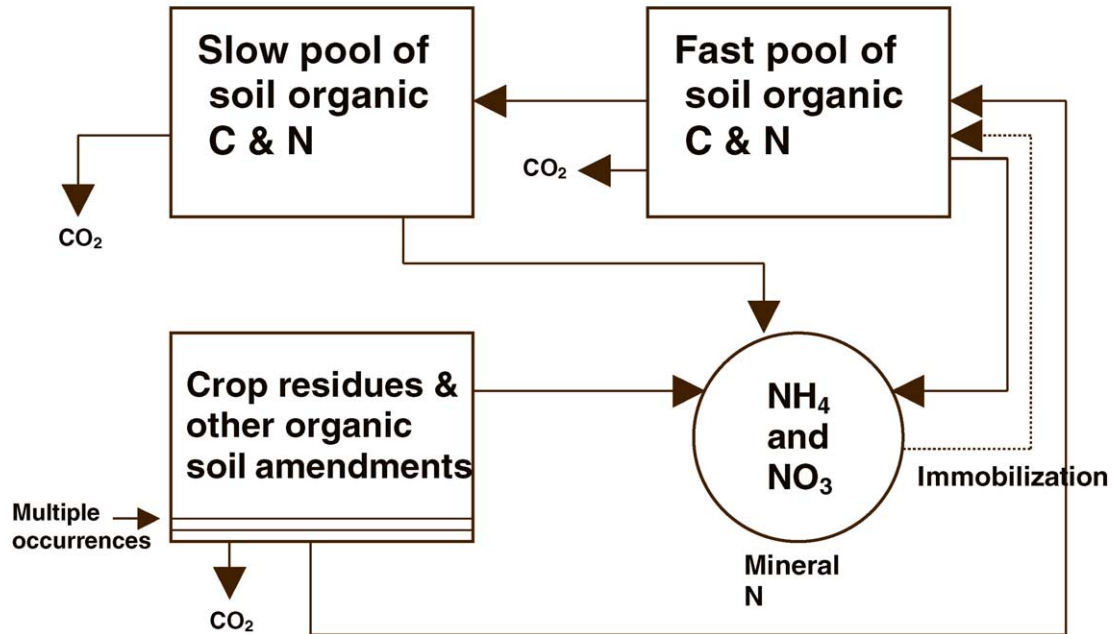


Fig. 4. Soil organic matter (SOM) and residue mineralization in GPFARM.

where NOMR is the ammonium-N mineralized (kg/ha/time step), k_{omr} is the first-order rate coefficient (fast or slow pool), and SOM is soil organic matter (kg/ha). The fraction of carbon in the SOM is 0.58 and the C:N ratio is 10. Factors for temperature stress (TFAC) and water stress (WFAC) are calculated using the relationships described in [Shaffer et al. \(2001\)](#). Transfer from the fast to slow organic matter pools is accomplished using a transfer coefficient currently defaulted to 0.0635 in GPFARM 2.0 soil profiles. Net sequestration of SOM and associated carbon occurs when mineralized organic residues are added to the two-pool system at rates faster than SOM decay ([Fig. 4](#)).

2.3.2. Mineralization of crop residues, manure, and other organic matter

Mineralization of crop residues and other organic materials such as manure to form $\text{NH}_4\text{-N}$ ([Fig. 4](#)) is computed using the following equations,

$$\text{CRES} = \text{fr} \times \text{RES}, \quad (10)$$

where RES represents the dry residues (kg/ha), fr is the carbon fraction of the residues, and CRES is the carbon content of the residues (kg/ha),

$$\text{CRESR} = k_{\text{resr}} \times \text{RADJST} \times \text{CRES} \times \text{TFAC} \times \text{WFAC}, \quad (11)$$

where CRESR is the residue carbon metabolized (kg/ha per day), k_{resr} is the first-order rate coefficient (day^{-1}), and RADJST is the rate adjustment factor depending on the current C:N ratio. RADJST is set equal to 1.0 at a base C:N of 25; to 2.6 at C:N equal to 9; to 0.29 at C:N equal to 100; and to 0.57 at C:N equal to 40. Linear interpolation is used between these points. Transfer of decayed residue material to the fast N_0 pool occurs at a C:N ratio of 6.5 for manure and other organics, at 10 for crop residues starting at <25 , and at 12 for crop residues starting at ≥ 25 .

The mineralization of manure and other organic wastes is calculated using the same basic equation set for crop residues given above, with manure or organic wastes substituted for crop residues. Each application of organic residues is tracked individually until it is added to the fast SOM pool ([Fig. 4](#)). This avoids the problem of having mixed residues with different decay ages in the same pool set.

2.3.3. Nitrification

Daily nitrification of $\text{NH}_4\text{-N}$ is calculated using,

$$\text{N}_n = k_n \times \text{TFAC} \times \text{WFAC}, \quad (12)$$

subject to the constraint $\text{N}_n \leq \text{NAF}$, where k_n is the zero-order rate coefficient for nitrification (kg/ha per day), TFAC is the temperature stress factor (0–1), WFAC is the soil water stress factor (0–1), and NAF is the ammonium-N content of the top 30 cm (kg/ha).

2.3.4. Denitrification

N lost to denitrification (N_{det}) is computed using the equation,

$$\text{N}_{\text{det}} = k_{\text{det}} \times \text{NIT1} \times \text{TFAC} \times [\text{NWET} + \text{WFAC} \times (1 - \text{NWET})], \quad (13)$$

subject to the constraint, $\text{N}_{\text{det}} \leq \text{NIT1}$, where N_{det} is nitrate-N denitrified (kg/ha per day), k_{det} is the rate constant for denitrification, NIT1 is the nitrate-N content of the top 30 cm

(kg/ha), and NWET is either 1 or 0 depending on whether a precipitation or irrigation event has occurred. Eq. (13) has the advantage that maximal denitrification is simulated on the wet days, while a separate estimate of denitrification under dryer soil water conditions is made for other days. The value assigned to k_{det} is a function of percent soil organic matter, soil drainage class, type of tillage, presence of manure, tile drainage, type of climate, and occurrence of pans (Shaffer et al., 1991).

2.3.5. NH_3 volatilization

Daily nitrogen lost to NH_3 volatilization (N_{NH_3}) is calculated using,

$$\text{N}_{\text{NH}_3} = k_{\text{af}} \times \text{NAF} \times \text{TFAC}, \quad (14)$$

subject to the constraint, $\text{N}_{\text{NH}_3} \leq \text{NAF}$, where N_{NH_3} is ammonia-N volatilized (kg/ha per day), k_{af} is the rate constant for ammonia volatilization, and NAF is the ammonium-N content of the top 30 cm (kg/ha). The particular value used for k_{af} is a function of fertilizer application method, occurrence of precipitation, cation exchange capacity of surface soil, and percent residue cover (Shaffer et al., 1991). In the case of manure, k_{af} is a function of the type of manure and application method (Shaffer et al., 1991).

2.4. Other GPFARM simulation modules

Other science modules include evapotranspiration (Farahani and Ahuja, 1996; Farahani and DeCoursey, 2000), weed impacts on crop yield (Canner et al., 1998, 2002), water/solute transport and soil properties (Nachabe and Ahuja, 1996; Ahuja et al., 2000), forage and animal production (Hanson et al., 1992), and soil loss due to wind and water erosion (Ascough et al., 1995, 1997).

3. Field methods

Field plot studies were conducted in Fort Collins, Colorado, USA from 1989 through 1991. The objective of the study was to provide test data to determine the relative contributions of management practices to corn yield and residual soil $\text{NO}_3\text{-N}$ concentrations. Management practices included irrigation, nitrogen fertilization, and corn and redroot pigweed (*Amaranthus retroflexus* L.) plant populations. The soil was a Nunn clay loam (Aridic Argiustolls; fine, montmorillonitic, mesic) with 2.5% organic matter and a pH of 7.7. Individual plots eight rows wide (75 cm row spacing) by 7.5 m in length were established in the same locations each year. The experimental site was moldboard plowed each autumn to a depth of 25 cm, and disked to prepare the seedbed before spring planting. In 1989 and 1990, corn monoculture plots were treated with a pre-emergence herbicide mix of cyanazine and metachlor each at a 2.2 kg/ha a.i. rate. In 1991, weed control was accomplished entirely by hand weeding. Corn (variety Pioneer 3906) was planted each year during the first week of May.

The experimental design was a split-plot with four replications, with irrigation being the main-plot and N fertilizer and plant population being the sub-plot factors. The six treatments used in this paper were from the corn monoculture (weed-free plots) and included (1) a fully

irrigated and fully nitrogen fertilized treatment (denoted fert_irr), (2) a minimal irrigation but full nitrogen treatment (denoted fert_minirr), and (3) a full irrigation, but no nitrogen treatment (denoted nonfert_irr). Each irrigation and N fertilizer treatment combination was for either high or low corn plant densities.

Urea (46-0-0) was applied at a rate of 200 kg/ha N prior to spring disking for fertilization treatments. After emergence, corn seedlings were thinned to 85,000 plants/ha for the low corn density treatment and 115,000 plants/ha for the high corn density treatment. Irrigation practices varied with year. In 1989 and 1990, plots receiving full irrigation were furrow irrigated when soil moisture was approximately 50% depleted to a depth of 120 cm as determined by neutron gauge measurements (Campbell Pacific Nuclear Corp. Model #503 hydroprobe). Minimal irrigation plots received irrigation at 70% soil moisture depletion. Once the first few plots of the row reached 50 or 70% water depletion, all plots in the row received irrigation. In 1991, the fully irrigated plots were irrigated based on the appearance of visible stress in the plants throughout the row, and the minimal irrigation plots received supplemental water only when complete crop failure from drought appeared imminent. In 1989, the fully irrigated treatments received irrigations in June and July, and the minimal irrigation treatment received irrigation in July. In 1990, the fully irrigated treatments received irrigations in June and July, and the minimal irrigation treatment received a supplemental watering in late June. In 1991, the fully irrigated treatments received a single irrigation on June 30 and the minimal irrigation treatments were irrigated on July 8. Irrigation events for the fully and partially irrigated treatments are summarized in Fig. 5 along with daily precipitation.

Corn grain yield was measured by hand harvesting all ears from the two center rows of each plot, separating the grain with a hand crank corn shelling device, obtaining grain weight,

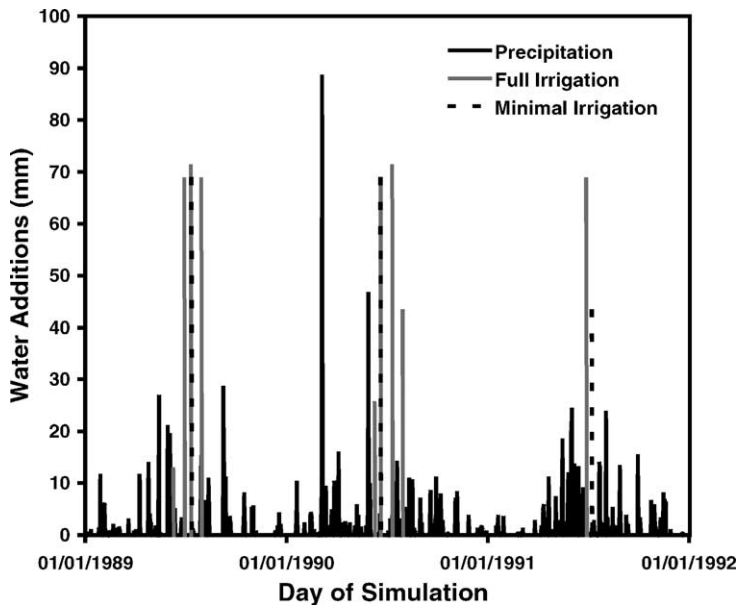


Fig. 5. Seasonal irrigation and precipitation for South farm field study January 1989 through December 1991.

determining grain moisture gravimetrically, and expressing yields in kg/ha on a dry matter basis. After corn harvest each year, one 4 cm diameter by 150 cm deep soil core was taken from the approximate center of each plot within the corn row using a hydraulically driven soil sampler. Each core was divided into 30 cm increments. Samples were air dried and soil $\text{NO}_3\text{-N}$ determined using a KCl extraction procedure (Keeney and Nelson, 1982). Soil $\text{NO}_3\text{-N}$ concentrations were converted to kg/ha units and adjusted for soil bulk density. Some additional details about the field study and its application to simulation of corn-pigweed (*Amaranthus* sp.) competition can be found in Ball and Shaffer (1993).

4. Model simulation runs

GPFARM DSS version 2.0, which includes GPFARM Science Simulation version 2.04 and GPFARM Databases version 2.0, was used to simulate corn yields and residual $\text{NO}_3\text{-N}$ for 1989, 1990, and 1991. Model coefficients included with version 2.0 were used to make the simulations. The crop coefficients for irrigated corn were selected for use with the Pioneer 3906, a variety designed for irrigation. A management unit land area was set up for each management treatment in the study. Individual plots were not simulated due to the lack of detailed experimental information on plot surface characteristics, soil attributes, and topography. Table 1 summarizes the management treatments simulated and includes full and minimal irrigation, fertilized and non-fertilized, and low and high corn populations. GPFARM irrigation options use the amount of water applied as 100% efficient in its application with a default sprinkler irrigation system. Irrigation can be entered for each event or scheduled at a time interval, but cannot be implemented on a soil water depletion rule as in this field study. Therefore, each irrigation event was entered amount water applied (100% efficient) in Fig. 5. Applied water was derived from records on total water applied and adjusted for the efficiency of the furrow irrigation which was calculated based on measured values for runoff. A historical climate file for Fort Collins, CO was used in the simulation. Fig. 5 shows the daily precipitation and irrigation events from January 1989 through December 1991. The model was initialized in November 1988 with soil water content set at field capacity for the default soil Nunn clay loam loaded from the GPFARM

Table 1
Treatments simulated with the GPFARM model

Treatment code	Definition
Fert_irr_h	Fertilized with 200 kg/ha urea-N, irrigated, high corn population of 115,000 plants/ha
Fert_minirr_h	Fertilized with 200 kg/ha urea-N, minimal irrigation, high corn population of 115,000 plants/ha
Nonfert_irr_h	Nonfertilized, irrigated, high corn population of 115,000 plants/ha
Fert_irr_l	Fertilized with 200 kg/ha urea-N, irrigated, low corn population of 85,000 plants/ha
Fert_minirr_l	Fertilized with 200 kg/ha urea-N, minimal irrigation, low corn population of 85,000 plants/ha
Nonfert_irr_l	Nonfertilized, irrigated, low corn population of 85,000 plants/ha

soils database. The soil profile was limited to a 152 cm depth, as that was the extent of the soil field tested. Initial residual $\text{NO}_3\text{-N}$ values for each soil layer were set from November 1988 field soil tests. A continuous simulation was then made for the years of the study from November 1988 through December 1991.

5. Statistical methods

The SAS statistical package was used for all analyses (SAS Institute Inc., 1999–2001). Linear regression analyses evaluated observed versus simulated treatment means for corn yields and soil residual $\text{NO}_3\text{-N}$. A paired *t*-test was used to test the slopes and y-intercepts of the fitted lines through the data points for statistical deviation from 1 and 0, respectively. SAS was also used to calculate standard deviations for the observed treatment means along with root mean square error (RMSE), sum of the residuals (SRES), sum of the absolute residuals (SARES), and mean error (bias) for simulated versus observed values for mean corn yields and mean soil residual $\text{NO}_3\text{-N}$ (McMaster et al., 1992). An extended modeling error (EME) method was developed and applied to help separate modeling error from experimental error. This method is similar to that proposed by Hansen et al. (2001) developed to separate the measurement uncertainty from the model errors. This was done by taking the absolute difference between the closest end point of the standard deviation and the corresponding simulated value. Simulated points that overlapped ± 1 standard deviation from the observation were assigned zero simulation error. All the absolute differences were then averaged to give a mean extended modeling error (EME).

6. Results and discussion

Temporal trend comparisons of simulated and observed results for corn grain yields (Fig. 6a and b) and soil residual $\text{NO}_3\text{-N}$ (Fig. 7a and b) for continuous modeling of years 1989 through 1991 under the high corn population treatment (a) and the low corn population (b) are shown. The error bars show the standard deviations of the field plot observations.

Poor corn growing conditions in 1991 from early weed competition and lack of available irrigation water resulted in lower observed grain yields in all treatments compared to previous years (Table 2). Archived notes showing a change in field plot managers, weed control technique and a different irrigation technique which resulted in 68.5 mm irrigation water applied in 1991 mm versus 221 mm (1989) and 208 mm (1990) were contributing factors. Observed means for corn grain yields and residual $\text{NO}_3\text{-N}$ for the high and low corn plant populations were not significantly different for any treatment ($P < 0.05$). Model results also showed minimal effects of plant population on yield and residual $\text{NO}_3\text{-N}$. Some population dynamics would be expected, but apparently the impacts were within the experimental error of the study.

Observed grain yields (Fig. 6a and b) trended downward during 1989 and 1990 due to decreasing growing season precipitation, and the trend continued in 1991 from problems with water and pest management. The model results also exhibited this same trend. In 10 out of 18 cases, the model corn grain results were within 1 standard deviation of the

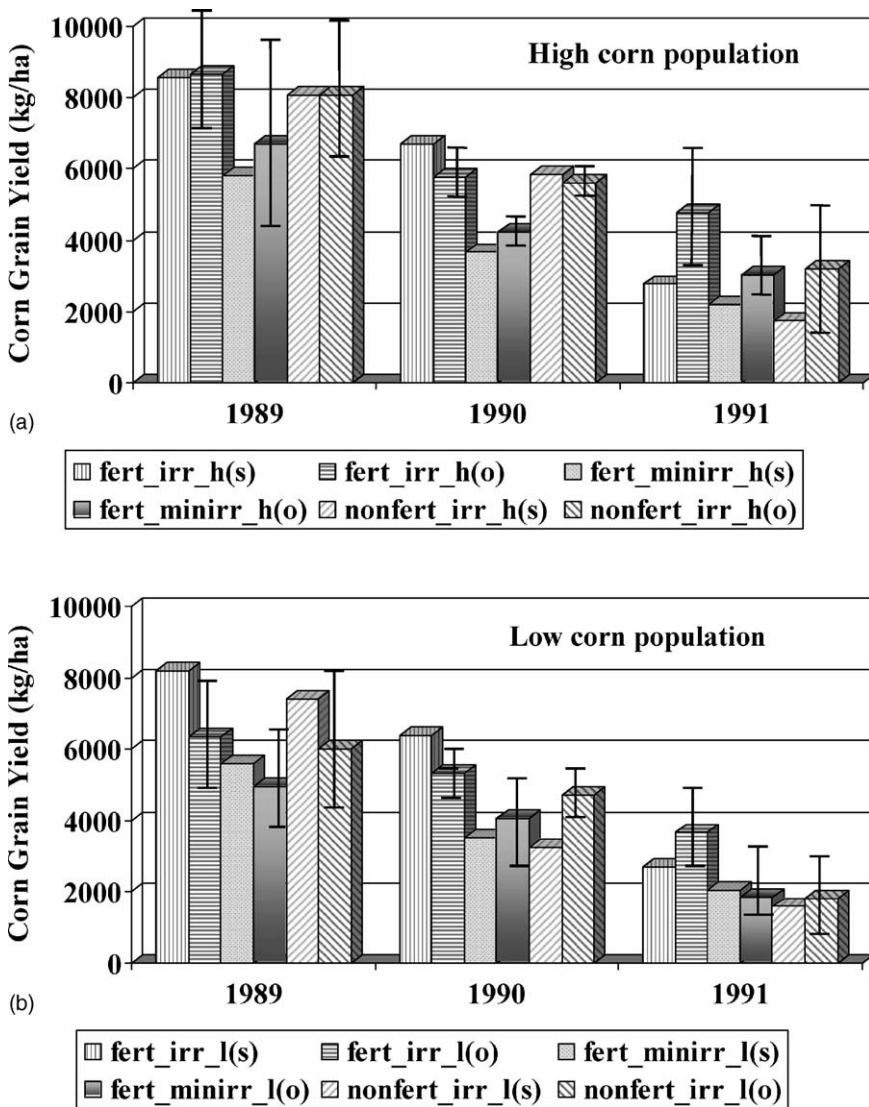


Fig. 6. Simulated (s) and observed (o) corn grain yields, 1989–1991, for high (a) and low (b) corn population. Error bars represent standard deviations for observations.

observed means (Table 2). High standard deviations indicate high variability among plots within the treatment but little archive information is available to explain this. In general, higher field variability between plots was probably due to previous plot area usage of organic fertilizers, invasive weed pressures from adjacent corn/pigweed treatment plots, and variation in irrigation water delivered along furrows resulting in more water stress in some plots than others. Lack of weed scouting records prohibited use of the GPFARM weeds

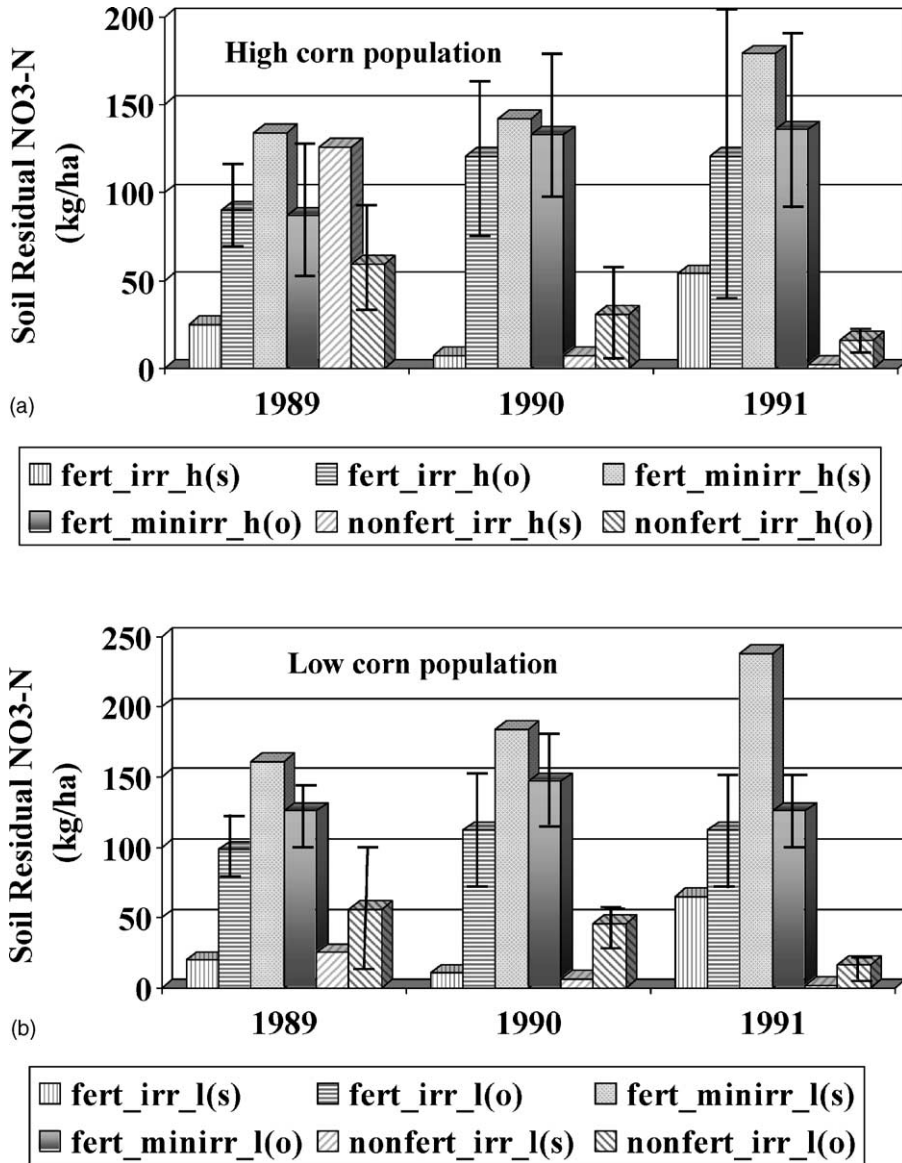


Fig. 7. Simulated (s) and observed (o) soil residual $\text{NO}_3\text{-N}$, 1989–1991, for high (a) and low (b) corn population. Error bars represent standard deviations for observations.

module which would project yield loss due to weed pressures. In addition, the variation in water delivery control in the furrows contributed to uncertainty in the amount water applied, an input for the GPFARM irrigation event system that currently uses sprinkler as a surrogate for furrow irrigation.

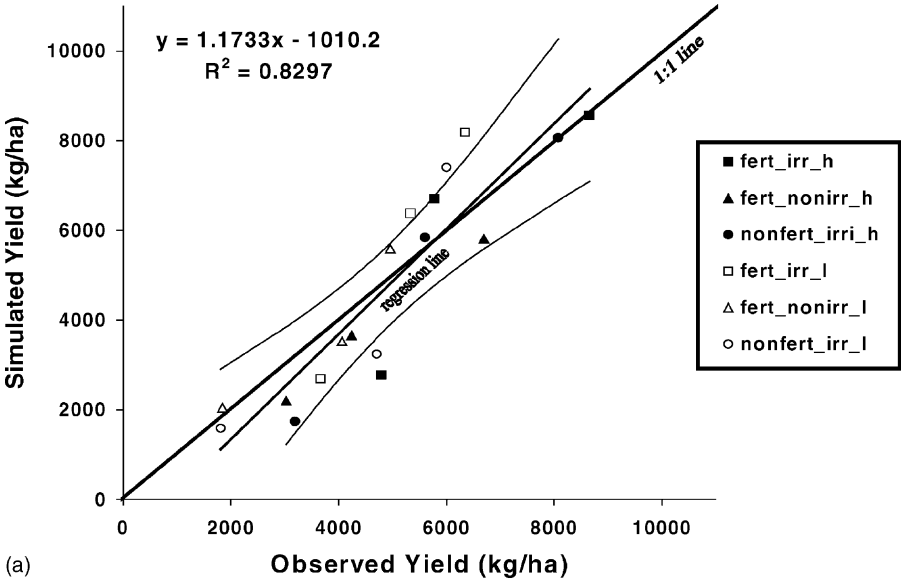
Table 2

Predicted and observed corn yields, observed standard deviations, and extended modeling error (EME)

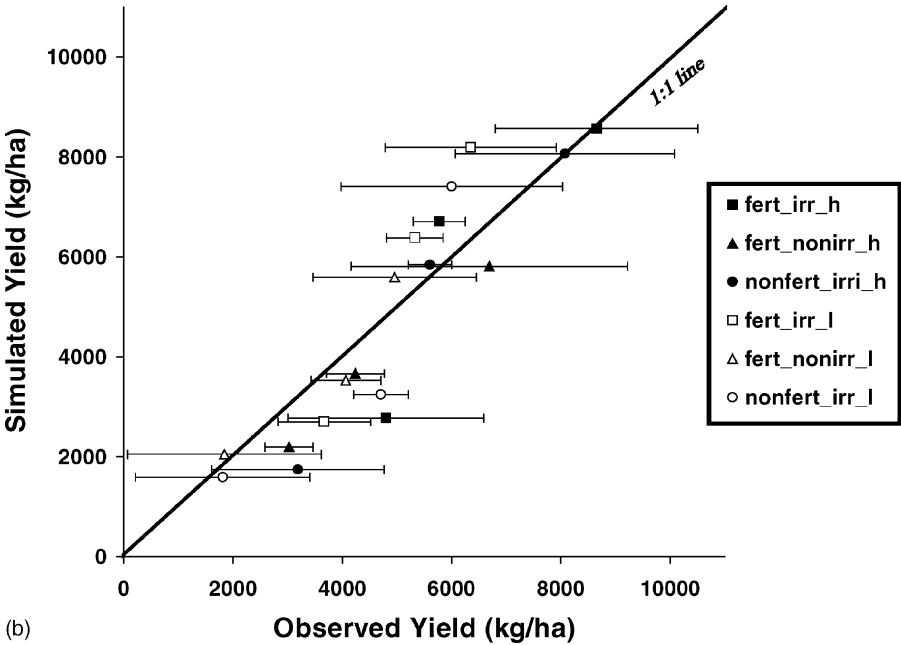
Year	Treatment code	Predicted yield (kg/ha)	Observed yield (kg/ha)	Observed S.D. (kg/ha)	Extended modeling error (kg/ha)
1989	Fert_irr_h	8560	8660	1860	0
1989	Fert_minirr_h	5810	6690	2530	0
1989	Nonfert_irr_h	8060	8080	2000	0
1989	Nert_irr_l	8190	6350	1570	270
1989	Fert_minirr_l	5590	4960	1500	0
1989	Nonfert_irr_l	7400	6000	2020	0
1990	Fert_irr_h	6710	5780	475	455
1990	Fert_minirr_h	3660	4240	529	51
1990	Nonfert_irr_h	5840	5600	399	0
1990	Fert_irr_l	6380	5330	519	531
1990	Fert_minirr_l	3520	4060	639	0
1990	Nonfert_irr_l	3240	4710	498	972
1991	Fert_irr_h	2770	4790	1790	230
1991	Fert_minirr_h	2190	3020	439	391
1991	Nonfert_irr_h	1740	3190	1580	0
1991	Fert_irr_l	2690	3670	852	128
1991	Fert_minirr_l	2050	1840	1770	0
1991	Nonfert_irr_l	1590	1810	1600	0
Mean					168

Observed soil residual $\text{NO}_3\text{-N}$, Figs. 7a and b, showed a slight visual trend for the fertilized treatments with the $\text{NO}_3\text{-N}$ values increasing over the 3 years. This trend can be explained by the decrease in crop yield with accompanying reduction in crop nitrogen uptake. As expected, the observed non-fertilized treatment showed a steady decrease over the same time frame. The agreement of the model residual $\text{NO}_3\text{-N}$ results with the observations was not as good as with the corn yields, and only 5 of 18 residual $\text{NO}_3\text{-N}$ values were within 1 standard deviation of the observations (Table 3). Initializing residual soil nitrates for a treatment and use of the model default value for percent readily mineralizable nitrogen (N_0) not adjusted for organic history across the plots may have contributed to model input error. However, the visual trends of the model results were in the same general direction as the observed values for all treatments, regardless of population size.

Comparisons of pooled observed and simulated results for all treatments composited over the 3-year study for corn yield and soil residual $\text{NO}_3\text{-N}$, are shown in Figs. 8a and 9a, respectively. The 1:1 lines represent perfect agreement between the simulated and observed values. A linear regression was run on each data set with the simulated results as the dependent variable (Y -axis). Results from a two-tailed, paired t -test showed that the intercepts (yield, $t = -1.44$; $\text{NO}_3\text{-N}$, $t = 0.460$) and slopes (yield, $t = 1.30$; $\text{NO}_3\text{-N}$, $t = 0.400$) of these regression lines were not different from 0 and 1, respectively, at the $P < 0.05$ level. The R^2 values of 0.830 and 0.383 for the crop yields and soil residual $\text{NO}_3\text{-N}$, respectively, demonstrate the level of scatter seen in these results. The differences between simulated and observed corn yields are similar to those found with related studies that have applied GPFARM to both dryland and irrigated conditions (McMaster et al., 2002b; Andales et al.,

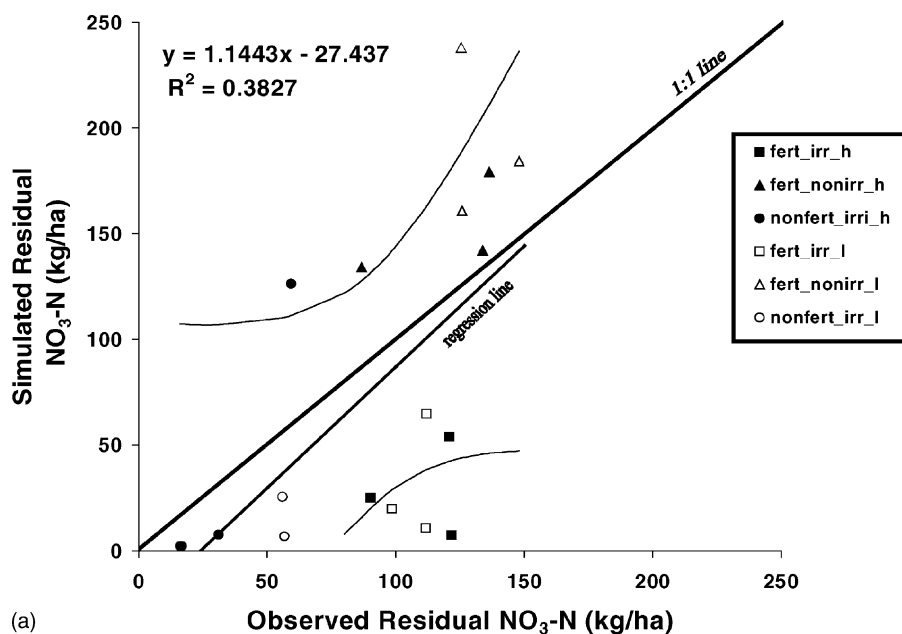


(a)

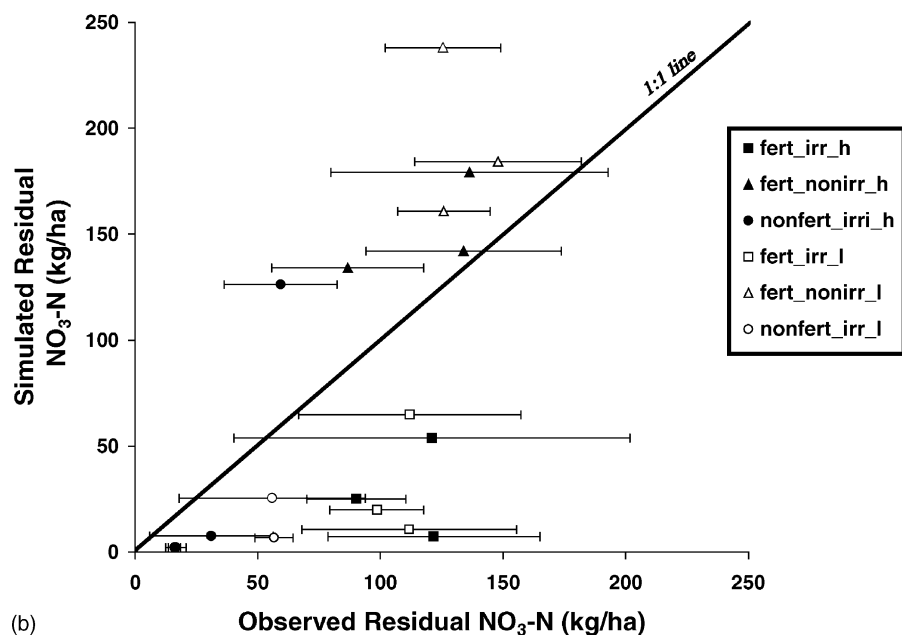


(b)

Fig. 8. Pooled regression of simulated vs. observed corn grain yield (a), and standard deviations for observed grain yield (b) for all treatments, 1989–1991, South farm study.



(a)



(b)

Fig. 9. Pooled regression of simulated vs. observed soil residual $\text{NO}_3\text{-N}$ (a), and standard deviations for observed residual $\text{NO}_3\text{-N}$ (b) for all treatments, 1989–1991, South farm study.

Table 3

Predicted and observed residual NO₃-N in the profile for each treatment along with observed standard deviations and extended modeling errors (EME) in plot NO₃-N

Date	Treatment code	Predicted residual NO ₃ -N (kg/ha)	Observed residual NO ₃ -N (kg/ha)	Observed S.D. (kg/ha)	Extended modeling error (kg/ha)
24 October 1989	Fert_irr_h	25.1	90.2	20.3	44.8
	Fert_minirr_h	134.0	86.7	30.9	16.4
	Nonfert_irr_h	126.0	59.3	23.1	43.6
	Fert_irr_l	19.9	98.6	19.2	59.5
	Fert_minirr_l	161.0	126.0	18.9	16.1
	Nonfert_irr_l	25.4	55.9	37.9	0.0
28 November 1990	Fert_irr_h	7.4	121.0	43.1	70.5
	Fert_minirr_h	142.0	133.0	39.8	0.0
	Nonfert_irr_h	7.6	30.8	25.2	0.0
	Fert_irr_l	10.7	112.0	43.8	57.5
	Fert_minirr_l	184.0	147.0	33.9	3.1
	Nonfert_irr_l	6.8	45.8	7.8	31.3
12 November 1991	Fert_irr_h	53.8	121.0	80.7	0.0
	Fert_minirr_h	179.0	136.0	56.5	0.0
	Nonfert_irr_h	2.2	16.1	2.5	11.4
	Fert_irr_l	64.9	112.0	45.3	1.8
	Fert_minirr_l	238.0	126.0	23.6	88.4
	Nonfert_irr_l	2.2	16.6	4.2	10.2
Mean					25.2

1992). The scatter in the soil residual NO₃-N is higher than normally expected with models similar to GPFARM (Hansen et al., 2001; Shaffer, 2002). Both R^2 values were significant at the $P < 0.05$ level with 18 data points. Deviations from the 1:1 line are a combination of experimental error (systematic and random) in the measurements and errors in the model (conceptual errors, input data errors, and uncertainty in parameter values) (Shaffer, 1988; Shaffer and Delgado, 2001; Hansen et al., 2001). The solid curved lines in Figs. 8a and 9a represent the 95% confidence bands for the regressions and give a sense of the general reliability of the model simulations. RMSE, SRES, and SARES statistics computed for the pooled 3-year data sets were 1,030, 2,070, and 15,200 kg/ha, respectively, for the corn yields and 63.4, -12.1, and 848 kg/ha, respectively, for the soil residual NO₃-N. The mean error or bias was computed by dividing the SRES values by, the number of observations ($n = 18$) giving 145 kg/ha for the corn yield and -0.67 kg/ha for the soil residual NO₃-N. In both cases, the bias was not different from zero at the ($P < 0.05$) level. These statistics provided additional evidence that the model simulated results were not trending high or low with respect to the observations.

The error bars shown in Figs. 8b and 9b represent ± 1 standard deviation in the experimental observations. These results illustrate the degree of uncertainty in the observations and indicate whether the deviations from the 1:1 line can be explained by experimental error alone. For both corn yield and soil residual NO₃-N, measurement uncertainty involving a combination of systematic and random errors explained some but not all of the scatter in the

simulated results around the 1:1 lines, Figs. 8a and 9a. Tables 2 and 3 show the individual extended modeling error values (EME). Crop yield EMEs range from 0 to 455 kg/ha with a mean of 168 kg/ha. Soil residual $\text{NO}_3\text{-N}$ EMEs range from 0 to 88.4 kg/ha with a mean of 25.2 kg/ha. For soil residual $\text{NO}_3\text{-N}$, mean EMEs were similar across the three study years giving 30.1, 27.2, and 18.6 kg/ha for 1989, 1990 and 1991, respectively. Mean EMEs for crop yields displayed more variability with values of 45.0, 335, and 125 kg/ha for 1989, 1990, and 1991, respectively. The EME method has the characteristic of presenting lower values as the measurement error increases and will equal zero at high enough experimental validation error relative to model error. The technique does, however, provide an important indication of the magnitude of modeling error relative to validation measurement error. For this study, mean EME represented 19.9% of the mean absolute residual error (SARES/ n , $n = 18$) for the crop yields and 53.5% for the mean absolute residual error for $\text{NO}_3\text{-N}$.

7. Conclusions

Simulated versus observed data for a 3-year irrigated field study indicated that the GP-FARM decision support system could simulate corn yields and residual soil $\text{NO}_3\text{-N}$ that are not biased at the $P < 0.05$ level with a mean extended modeling error (EME) of 168 and 25.2 kg/ha for corn yields and soil residual $\text{NO}_3\text{-N}$, respectively. Differences observed between simulated and observed corn yields were similar to related studies that applied GPFARM to both dryland and irrigated conditions. The scatter in the soil residual $\text{NO}_3\text{-N}$ is higher than normally expected with models similar to GPFARM and an EME technique was used to separate experimental from modeling error. The mean EME values for residual $\text{NO}_3\text{-N}$ of 53.5% of mean SARES compared to 19.9% for the corn yields demonstrated greater modeling error for residual $\text{NO}_3\text{-N}$ than yield. Variability in the experimental field data probably played a significant role by increasing the variability of the model input data for initial soil residual $\text{NO}_3\text{-N}$ (model error) as well as the variability of the soil $\text{NO}_3\text{-N}$ validation data (experimental validation data error). Both types of error played roles in this study and reemphasized the importance of good field data in modeling studies.

Future model enhancements were suggested as a result of this study. They include adding a rule-based irrigation system responsive to soil water depletion level, adding a furrow irrigation system option, adding advanced features to allow adjustment of percent material in N_0 pools in soils with organic nutrient application histories, and improvements in the crop model response to stress via temperature, nitrogen, water, and their interactions.

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